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THE SHAPED CHARGE CONCEPT
PART II. THE HISTORY OF SHAPED CHARGES

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U.S. ARMY LABORATORY COMMAND

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This article is the second of a three part series on hollow charges and shaped charges. This part depicts the history of shaped charges from their early beginning through the post World War II era.

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1. INTRODUCTION

The term "shaped charge" is applied to explosive charges with lined or unlined cavities. The cavity is formed in the end of the explosive charge opposite the point of detonation. The term "shaped charge," however, has a more general meaning, e.g., in Cook (1958). The shaped charge is sometimes referred to as the hollow charge (in the U.K. and the U.S.), the cumulative charge (in the USSR), or the Hohlladung (in Germany).

2. HISTORY

The history of shaped charge conception and development is wrought with controversy. In 1792, the mining engineer, Franz von Baader (1792), allegedly noted that one can focus the energy of an explosive blast on a small area by forming a hollow in the charge. Lenz (1965) stated that Baader, in 1799 (not 1792!), observed that if depressions or shapes were cut in an explosive and placed face down on a steel plate, the detonation would cause these shapes to appear on the plate. This is known as explosive engraving. D. R. Kennedy (1983) presents additional information on the life of von Baader and his version of the history of the shaped charge effect. Other historical accounts are given in Berkholtz (1988) and in Walters and Zukas (1989).

The original von Baader (1792) paper, however, primarily discussed bore hole drilling and loading, confinement effects on propellants, the positioning of a small air cavity between the explosive powder and the tamping (at best, a standoff distance effect), and rock fragmentation. His original paper did not discuss explosive engraving or hollow cavity charges. However, this is a moot point since von Baader used black powder in his experiments which is not capable of detonation or shock formation. Actual shaped charge devices were made possible by the discovery of blasting caps (detonators) by Alfred Nobel (Mohaupt 1966; E. I. du Pont 1980) in 1867. The explosive reaction initiated by these blasting caps could propagate through a column of explosive without the use of confinement. This was termed "detonation" or "brisant explosion." Thus, the first demonstration of the hollow cavity effect for high explosives was achieved by von Foerster (sometimes spelled Forster, the correct spelling being Forster with an umlaut over the "o" which may be written as "oe") in 1883 (von Foerster 1883, 1884). A translation of some of Lieutenant von Foerster's work is given in Wisser (1886). Quoting from von Foerster (Wisser 1886):

> "If a coin be placed between a gun cotton cartridge and a wrought-iron plate, the figures and letters in relief on the coin will appear in the iron as depressions after the explosion; if, instead of the coin, a green leaf be inserted, the entire skeleton of the leaf will appear

> on the iron plate after the explosion. The more prominent, as well as the finer veins, protect the underlying iron, the more delicate parts of the leaf, lying between the veins, cannot afford the same protection; hence, the depression under the latter is the greater."

Again, this is a form of explosive engraving. Kennedy (1983), Freiwald (1941), Schardin (1954), and Berkholtz (1988) provide further detail on the discoveries of von Foerster and conclude that he was the true discoverer of the modern hollow charge.

Also, Gustov Bloem (1886) of Dusseldorf patented a shell for detonating caps which resembles a shaped charge with a hemispherical liner.

The hollow cavity (i.e., unlined shaped charge) was rediscovered by Charles E. Munroe of the Naval Torpedo Station, Newport, Rhode Island. Munroe's discoveries date from 1888 and are well documented (Munroe 1888a, 1888b, 1888c, 1894, 1900). The hollow charge or cavity effect is known in the U.S. and U.K. as the Munroe Effect.

Munroe (1888c) detonated blocks of explosive in contact with steel plates. The explosive charge had the initials U.S.N. (United States Navy) inscribed on the charge opposite the point of initiation. These initials were reproduced on the steel plate. Munroe further observed that when a cavity was formed in a block of explosive, opposite the point of initiation, the penetration, or depth of the crater produced in the target, increased. In other words, a deeper cavity could be formed in a steel block using a smaller mass of explosive! In Munroe's own words:

> "We have offered as an hypothesis to explain this phenomenon that, where spaces exist between the gun cotton and the iron, portions of the undetonated gun cotton, or of the products of the explosion, the indentions are produced by the impact of these moving particles. We have devised many experiments to test this theory, and all have tended to confirm it. Among others we have bored deeper and deeper holes in the gun cotton, until we have completely perforated it, and the indentations made in the iron plates have increased with the depth of the hole in the gun cotton disk until, when the hole was bored completely through the gun cotton, we succeeded in completely perforating the iron plate." (Munroe 1888c; Clark 1948)

The increase in penetration results from the focusing of the explosive gases (detonation products) by the hollow cavity.

One of the first lined shaped charges (or perhaps the first shaped charge if we discount Bloem [1886]) was devised by Munroe (1894) and Clark (1948). This device consisted of a tin can with sticks of dynamite tied around and on top of it, with the open end of the tin can pointing downward. It was used to punch a hole through the top of a steel safe.

Early German reference to the hollow cavity effect, after von Foerster and Bloem, occurred in 1911-1912 patents in the U.K. and Germany by WASAG (Westfalische Anhaltische Sprengstoff Actien Gesellschaft) (1910, 1911). The WASAG patents clearly demonstrated the hollow cavity effect and the lined shaped charge effect. Also, M. Neumann (1911) and E. Neumann (1914) (who are often confused in the literature) demonstrated the hollow cavity effect. M. Neumann (1911) shows a greater penetration into a steel plate from a cylinder of explosive with a hollow, conical cavity (247 grams of Trinitrotoluol) than from a solid cylinder (310 grams of Trinitrotoluol).

This clearly illustrates what is known in the U.S. and Britain as the "Munroe Effect" and in Germany as the "Neumann Effect." The depth of the crater in the target can be further increased by displacing the hollow charge some optimal distance from the target, i.e., increasing the standoff distance, especially for a lined cavity charge. This situation was depicted graphically in Figure 4 of Part 1.

This effect was also illustrated in 1941 in Germany when a hollow cavity charge and a lined cavity charge detonated at a certain standoff distance above an armor plate were compared (OTIB 1941). The target plate was ship armor steel and the explosive mixture was 50% TNT and 50% cyclonite. The hollow cavity was a hemisphere with a cylindrical extension at its base equal to one-half of the diameter of the cavity (D). The liner was made of iron. The explosive contour was of the same geometry as the cavity and the explosive thickness was 0.15 times the cavity diameter. For the (unlined) hollow charge the penetration $P = 0.4D$ at zero standoff. For the lined cavity, $P = 0.7D$ at zero standoff, and $P = 1.2D$ for standoffs between 0.5 and 1.5D. For the iron-lined charge, D represents the inside diameter of the liner.

These formulae (OTIB 1941) are not accurate but are valid only for this particular experiment. They are not universal laws, but do illustrate the relative increase in performance in going from unlined to lined charges with a non-zero standoff distance.

Kennedy (1983) describes similar studies dated from 1913 to the early 1930s, concerned with the hollow cavity effect in mining and detonation devices.

Others, notably Baum et al. (1949) and Rollings et al. (1971), attribute the hollow cavity effect to

M. Sukhareskii (also transliterated as Sukhreski and Sucharewski), see Murphy (1983), for example. Indeed, Sukhareskii (1925) was the first known Soviet to investigate the shaped charge effect (in 1925-1926). He observed an increase in the explosive effect by a factor of 3 to 5. He also noted that the dimensions of the perforation achieved by hollow charges were proportional to the dimensions of the hollow cavity of the charge. Berkholtz (1988) and Schardin (1954) provide further detail on the life and results of Sukhareskii.

The first Italian paper on the shaped charge effect was by C. Lodati (1932). Apparently Schardin (1954) reviewed this work and reported that Lodati did not contribute anything new to the field.

Early British development of the hollow cavity charge was reported in Kline (1945). Eather and Griffiths (1983) of the U.K. provided a history of the U.K. contributions to the field of shaped charges which includes the achievements of Evans, Ubbelohde, Taylor, Tuck, Mott, Hill, Pack, and others. A. Marshall (1920) provides an early history of the unlined cavity charge and attributes its discovery to Munroe.

In the U.S., the contributions of Watson (1925) on percussion fuzes and Wood (1936) on self-forging fragments (also called explosively-formed penetrators, Misznay-Schardin devices, ballistic discs, or P-charge projectiles) were significant.

The Watson percussion fuzes, patented in 1925, used a parabola-shaped booster charge with a metal-lined hemispherical cavity, or "arched shield," to intensify the effect of the booster charge. Watson (1925) stated that the lined cavity effect required only one-fifth to one-sixth as much explosive as an unlined booster and the lined cavity charge would function over a "considerable air gap." This fuze is, in effect, a detonator using the shaped charge principle.

R. W. Wood (1936) of the Johns Hopkins University described what is known today as an "explosively formed penetrator." Wood's studies originated during his investigation of the death of a young woman who, on opening the door of a house furnace, was killed by a small particle of metal which flew out of the fire and penetrated her breast bone. The small particle of metal was from the coned end of a detonator which was apparently delivered with the coal from the mine. His paper also discussed the plastic flow of metals, deflagration, and detonation. Eichelberger (1954) credited Wood for recognizing the enhancement obtained by metal lined hollow charges.

Also, Payman and Woodhead (1937) of the U.K. reported observations of jets from the cavity in the ends of detonators. They attributed this jetting process to the "Munroe Effect."

The lined cavity shaped charge research accelerated tremendously between 1935 and 1950, due primarily to World War II and the application of shaped charges to the bazooka, panzerfaust, and other devices. The history of shaped charge development during this time frame is somewhat ambiguous in that the British, Germans, and U.S. all have made significant claims to the early development of modern lined cavity charges.

The discoverers of the modern lined cavity effect were Franz Rudolf Thomanek for Germany and Henry Hans Mohaupt, a Swiss, for the U.S.. Thomanek and Mohaupt independently perfected the hollow charge concept and developed the first effective lined cavity shaped charge penetrators.

Thomanek's early work dates from late 1935 to 1939 (Freiwald 19 ; Schardin 1954; Brandmayer and Thomanek 1943; Thomanek 1942, 1959, 1960, 1978; and Thomanek and von Huttern 1935). The Thomanek and von Huttern patent applications (approximately 1935) pertain to hollow charges, armor piercing shells, the shell nose design, high explosive mixtures and additives, techniques for casting high explosives, impact fuze systems, explosive initiation systems, shoulder-fired weapons, and small caliber, hand-held weapons. Unfortunately, this document is not dated by year, but the translator's note states, "(Partly before 1935?)."

Thomanek (1960) claims discovery of the hollow charge lining effect on 4 February 1938. Thomanek and von Huttern (1935) describe the tests and work conducted by Thomanek and his co-worker, Brandmayer.

Thomanek (1942) presents a detailed account of the hollow and lined cavity charge work he conducted from 1935 to 1941 in support of compensation he eventually received from the Reich. He credits Foerster with the first hollow charge work in 1883 and notes the contributions of WASAG and E. Neumann.

Thomanek reports that in 1935-36 an armor-piercing projectile with a hollow shaped charge was developed by the Army Weapons Office and patented by Captain Wimmer. The anti-tank rifle was demonstrated by Thomanek in the presence of Hitler in late 1935. Standoff effects, liner geometry, and liner materials were studied extensively from 1937 to the end of World War II (Walters and Zukas 1989; Thomanek 1942).

Thomanek and colleagues suspected that overlapping shock waves from the jetting of a hollow charge formed a new, more intense shock wave from the superposition of two primary shock waves. Thus, tests were performed with a glass-lined, evacuated cavity to determine the optimal air cavity pressure. In 1938, Thomanek and Schardin observed that glass lined shaped charges revealed superior performance due to the glass liner and not due to the evacuated cavity. Further studies concluded that iron and copper liners were especially suitable for increasing penetration (Schardin 1954).

Thomanek (1942) listed some of his most significant accomplishments during World War II as the development of: a casting device for hollow charges (patent applied for 10 August 1940); acute angle cone and liner with wall thickness for armor-piercing projectiles (patent applied for 9 September 1940); diaphragm-like liner for hollow charges (6 November 1940); and a hollow charge for rifle anti-tank land mines (29 May 1941).

Other German developments included steel liners (0.5- to 1.0-mm-thick) that were found to be superior to gray-iron casting (June 1940) and hollow charges with conical liners (up to 1.5-mm-thick and with angles between 20^0 and 45^0) which would perforate 15-mm armor plate at the proper standoff (25-30 mm). The charges used were cast. An increase of the diameter of the blast hole was made possible by the use of a bell-shaped, hollow charge which would also permit fewer irregularities than with the acute cone. The diameter was 1 cm (of the charge). The idea of firing a hollow charge shell from the shoulder was first conceived in 1937 (i.e., a rifle grenade).

Schardin (1954) noted that an exceptional degree of precision was required to guarantee the homogeneity of the jet from a shaped charge liner, especially the rotational symmetry of the liner wall thickness.

Schardin also reported on the early simulation of jet formation resulting from the impact of two streams of water. Also, experiments were conducted where a closed, conical glass container filled with air was plunged, apex first, into a tank of water. An explosive charge was detonated in the water below the apex of the glass cone. The resulting shock wave in water collapsed the glass liner and formed a jet of water similar to a hollow charge. The jet of water had a higher velocity than the water fountain formed from a simple underwater detonation without the glass liner.

The jet formed from a spinning shaped charge was also studied. It was observed that some jets formed from spinning shaped charges were tube-like in their structure, i.e., hollow. Water jets formed from impinging jet streams with rotating and tapered nozzles were shown to simulate this tube formation or hollow jets. It was also noted that jets from spinning shaped charges with hemispherical liners were less susceptible to spin effects (angular dispersion) than jets from conical shaped charge liners (Schardin 1954).

Schardin also reported on jet velocities of 90 km/sec resulting from symmetrically rotated shaped charges with beryllium liners. These charges were fired into a vacuum and were primarily in the gaseous phase.

L. Simon (1947) provides further detail on the German shaped charge studies during World War II and on the organization of the German military/industrial complex.

Mohaupt independently developed and introduced the shaped charge concept to the U.S.. Mohaupt's early work is given in Mohaupt (1966, 1941a, 1941b, 1947). Mohaupt's patent claimed a date of 9 November 1939 (Mohaupt, Mohaupt, and Kauders 1941a) .

Mohaupt, using lined cavity charges, designed practical military devices ranging from rifle grenades to mortars to 100-mm diameter artillery projectiles. These devices were test-fired at the Swiss Army Proving Ground at Thun, at Mohaupt's Laboratory, and at the French Naval Artillery Proving Ground at Gavre. These results were also demonstrated to the U.K. who then began development programs of their own, citing the U.K. WASAG patent as prior art (WASAG 1911). Following the early results of World War II, the French Government authorized the release of Mohaupt's information to the U.S. and in late 1940, tests were conducted at Aberdeen Proving Ground, Maryland, using several aspects of lined cavity shaped charges (Mohaupt 1966). The U.S. Ordnance Department had previously rejected a shaped charge munition presented by Nevil M. Hopkins, an American inventor. The Ordnance Department, however, used Hopkin's claim and the WASAG patent to lower Mohaupt's requested price of $25,000. The U.S. accepted the program, classified it, and thus excluded Dr. Mohaupt from the effort but produced the 2.36-inch HEAT machine gun grenade and the 75-mm and 105-mm HEAT artillery projectiles in 1941. Later, the machine gun grenade was modified to include a rocket motor and a shoulder launcher and became the bazooka. The bazooka was first used by the U.K. in North Africa in 1941. Other HEAT rounds were fired from tank mounted howitzers (Kennedy 1983, Mohaupt 1966). Berkholtz (1988), Green et al. (1955), and Watson (1950) provide additional detail on Mohaupt, Hopkins, and the use of HEAT rounds in World War II. Gray et al. (1947) also filed a U.S. patent (in 1941) on a shaped charge device during the same period as Mohaupt.

The anti-tank rocket weapons of World War II were pioneered by Dr. Robert H. Goddard who offered the Ordnance Department a series of tube launchers designed to fire rocket projectiles in 1918. Goddard died before receiving credit for his pioneering work, although the bazooka, adopted 24 years later, closely resembled his 1918 model. Dr. Hickman, a student of Robert Goddard, provided continuity to the studies that produced the anti-tank rocket weapon of World War II (Green et al. 1955). Incidently, Leslie Skinner, formerly of Aberdeen Proving Ground, has been called the "Father of the Bazooka." The Bazooka derived its name from a homemade trombone popularized by radio comedian Bob Burns (Weston 1985).

Kennedy (1983), Berkholtz (1988), and Walters and Zukas (1989) provide additional detail on bazookas as well as on the work of Thomanek and Mohaupt.

The German development of shaped charge warheads during the World War II period is discussed in Kennedy (1983, 1985), L. Simon (1947), Cave et al. (1945), Birkhoff (1947), Schumann (1945), OTIB (1941), Schardin (1954), Kline (1945), Thomanek (1942, 1960, 1978), and Thomanek and von Huttern (1935). Simon (1947) and Cave et al. (1945) entered Germany near the end of World War II to study and recover German technology. Simon (1947) reported on flash x-ray photographs in Germany including collapse studies of conical and hemispherical liners. Various other liner geometries were studied including helmet-shaped liners, bottle-shaped liners, and ellipsoidal liners. The effect of varying the cone angle, the wall thickness, and the standoff distance was studied for various shaped charges. Also, the effect of tapering the liner with respect to thickness was studied. The Germans concluded that 60/40 cyclotol (a RDX-TNT mixture) was the optimum explosive fill for shaped charges and aluminized explosives provided no additional advantage. According to Simon, the liner materials studied were steel, sintered iron, copper, aluminum, and zinc. It was realized that copper was the best liner material, but due to the shortage of copper in Germany, zinc liners were used instead.

Schumann (1941) reports on studies relating to standoff distance effects, explosive lenses, wave-shaping, and hemispherical liners. Schumann concluded that the hemisphere was an effective shaped charge liner geometry (actually a hemisphere with a cylindrical extension on its equator).

Wagner (1944) discussed the SHL (Schwere Hohlladung or heavy shaped charge). The SHL 500 was a 65-cm diameter shaped charge used against light ships. The SHL 1000 was apparently an improvement to the SHL 500. The largest SHL of this series was called the Beethoven and had a diameter of 180 cm with 5,000 kg of high explosive. The Beethoven was designed for use against ships and ground fortifications. During the Normandy invasion, the Beethoven destroyed two battleships and four large transport ships. The Beethoven was the forerunner of the MISTEL I and MISTEL II, which are discussed under shaped charge applications.

Wagner also discussed the development and production of other armor piercing, shaped charge projectiles

The hollow charge, or unlined shaped charge was first deployed on May 10, 1940 by the Germans on the Belgian fort of Eben Emael. The Germans, using 77 men, 10 gliders (costing about 77,000 deutschmarks) and 56 hollow charges, defeated 780 men defending the world's strongest fort. The fort fell in somewhat more than a day, but the decisive struggle took only 20 minutes (Mrazek 1970). The hollow charges were of two sizes, a 110-pound and a 25-pound charge. The hollow charges knocked out the steel cupolas (six-inches-thick) and observation turrets which led to the early demise of the Belgian defenses (Berkholtz 1988; Mrazek 1970).

The Germans were also instrumental in transferring hollow charge research to the Japanese. These is no evidence of hollow charge research in Japan before May 1942. At that time two German officers of the Army Weapons Office, Colonel Paul Niemueller and Major Walter Merkel, provided Japan with data and samples of the German 30- and 40-mm hollow charge rifle grenade. The Japanese officials involved were Lt. Col. Yoshitaka, the Japanese liaison officer for the Germans, and Col. A. Kobayashi, an explosives expert at the Second Army Arsenal in Tokyo (OTIR 1946). Other notable Japanese researchers were Futagami, Naruse, Nasu, Nagaoka, Nakiyama, and Lt. Gen. Kan. The hollow charges were presented as highly secret and valuable project and the Germans and Japanese continued to exchange shaped charge data until the cessation of hostilities in 1945.

The Japanese instigated a research and development program of their own and additional shaped charge designs were received from Germany. These designs included the panzerfaust and a large German hollow charge called the "MISTERIE?" (This is undoubtedly the MISTEL which evolved from the Beethoven charge discussed earlier). From the MISTEL, the Japanese developed the large SAKURA Bombs I and II for kamikaze attacks against warships which are discussed in Part 3.

In addition to the captured U.S. and British ammunition, and the information received from Germany, the Japanese did considerable independent research on shaped charges (OTIR 1946). This research included: gas flow and gas velocity from an unlined hollow charge; the jet velocity from a lined hollow charge; penetration versus standoff distance studies; hollow charge liner geometries varying from conical to hemispherical caps; various liner materials including mild steel, copper, aluminum, zinc, asbestos, molded bakelite, tin, and paper; recovery of jet particles in sand; and dynamic (missile) effects. The Japanese preferred laminated liners (three to seven sheets) over a single, homogeneous liner of the same thickness. The Japanese also concluded that a hole in the apex of a conical or hemispherical liner was desirable. Also, the size of this hole was critical, an optimal value for the apex hole diameter being one-tenth of the warhead charge diameter. (The wall thickness was taken as one twenty-fifth of the charge diameter and the liner diameter was taken to be four-fifths of the charge diameter for both conical and hemispherical liners). The optimal cone apex angle was determined to be between 35 to 50 degrees. Other tests used 9[illegible]-mm-diameter, soft steel, hemispherical liners with a 2.5-mm wall thickness. The optimal open apex diameter was concluded to be three-sixteenths of the charge diameter for this warhead.

Tapered liners were designed based on the 30- and 40-mm German rifle grenades. They used 19^0 conical steel liners tapered from 0.5 mm at the apex to 1.0 mm at the base. Other projectiles used constant wall thickness, laminated liners. The Japanese also developed torpedos, 18 inches and 12 inches in diameter using a tapered wall, 45^0 conical steel shaped charge liner with an open apex (OTIR 1946).

Other studies related to detonation physics and methods of focusing the gas flow, calculation of the target hole volume and penetration, penetration of concrete targets, and the recovery of jet particles by reducing the explosive power (mixing dynamite with starch to reduce the "strength" of the dynamite) and capturing the jet in sand (OTIR 1946).

The explosive charges used in research were spherical and formed from the arcs of two circles. Thus, the cross section of the charge looked like a new moon or quarter moon, etc., depending on the two radii used. Cylindrical, tapered, and boattailed explosive geometries were also studied as well as the effect of the high explosive head height and the length-to-diameter ratio of the charge. In fact, the height of the charge was varied from 0.5 of a charge diameter to 6 charge diameters. A charge height of 1.5 to 2 charge diameters was concluded to be optimal for a 80-mm diameter charge with a 64-mm diameter soft iron, hemispherical liner and with a 2.5-mm-thick wall (OTIR 1946).

Futagami (OTIR 1946) tested two-dimensional charges, i.e., a flat, disc-shaped charge confined between two lead plates. Tests of this nature were used to evaluate various liner materials, cone apex angles, liner wall thickness effects, and the effect of the diameter of the open apex region. All of the effects, including standoff distance studies, were also investigated with "three-dimensional" shaped charges. Futagami also studied bimetallic liners of soft iron and copper (the iron was in contact with the high explosive). As mentioned earlier, various liner materials were studied, including paper (of course, as stated in OTIR [1946], "...the paper shell is tore in pieces and flys away."). The Japanese also noted that any cavity existing between the liner and the explosive reduces the penetrating capability of the warhead.

The Japanese anti-tank shells, although not as effective as those developed by the Germans or the Allies, were used effectively on the Burma front. Other Japanese innovations (Kennedy 1983) included the suicidal "Lunge" mine which was, in fact, a shaped charge with a wooden handle used as an anti-tank weapon.

Some of the research conducted in the U.K. in the early forties is reported in Monro (1943). Monro describes the research of Evans, Ubbelohde, Lennard-Jones, Devonshire, and Andrew. The U.K. studied cadmium liners (which probably produce molten jets) and steel liners (where the jet is probably not liquid). Other topics, as pursued by the Germans, Japanese, and U.S. were also investigated. Monro reports on

U.S. weapons tests and on the evaluation of captured German shaped charges with aluminum, hemispherical liners and on Italian shaped charges using mild steel, parabolic liners. Tuck's (1943) work was also significant in the early forties.

The research and development in the U.S. in the 1940s is documented in Kennedy (1983), Birkhoff (1947), Cook (1958), and DM-1 (1947). DM-1 (1947) is an interesting history of weapons and demolition devices developed during World War II. Several topics are covered ranging from pocket knives to flame throwers to Bangalore Torpedos to shaped charges. A Bangalore Torpedo is a long, light steel tube loaded with explosives. It is essentially a pipe bomb. This device was invented during World War II by Major R. L. McClintock of the Queen Victoria's own Madras Sappers and Miners near Bangalore in Mysore, India (DM-1 1947). The Bangalore Torpedo was used to remove barbed wire entanglements, clear mine fields, and to insert into holes in fortifications made by shaped charge devices.

Shaped charge development, based on the early work of Mohaupt, was continued in the U.S. by the Du Pont Company, the Hunter Manufacturing Company, Croydon, Pennsylvania (for the M2 shaped charge), the Doblins Manufacturing Company, the Hercules Powder Company, the Atlas Powder Company, and the Corning Glass Company (for glass conical liners). This work was directed by the Board of Engineer Equipment or Engineer Board (EB). Research was conducted by Du Pont and the Eastern Laboratory at Gibbstown, New Jersey. Demolition charges such as the M1, M2, M2A3, M3, M3A, and others were tested at Aberdeen Proving Ground in 1942 and developed by the corporations cited above. A chronology of demolition shaped charge development from 1942 to 1946 is given in DM-1 (1947). Also, specifications for the M2A3 and the M3 shaped charge are given in DM-1 1947. The M3 weighs 40 pounds, 30 of which are high explosive and contains a welded steel cone that penetrates 60 inches of concrete. The M3 charge is 12.5 inches high and 9 inches in diameter. The M2A3 contains a glass, conical-shaped charge liner, it weighs 15 pounds with 11.5 pounds of explosive and can penetrate 30 inches of concrete. The M2A3 has approximately the same penetrating power as the M1, and further details are given in Part 3 where demolition charges are discussed.

In addition to the fundamental studies performed in 1941 at the Eastern Laboratory, E. I. Du Pont de Nemours and Company (Du Pont), parallel studies were undertaken by the Eastern Laboratory and Division 8, National Defense Research Committee, Bruceton, PA. The sponsor was the Office of Scientific Research and Development. The chief scientists at the National Defense Research Committee were G. B. Kistiakowsky, D. P. MacDougall, S. J. Jacobs, and G. H. Messerly (Cook 1958).

At the same time, E. M. Pugh organized a group at the Carnegie Institute of Technology. Following the war, the Carnegie Institute took over the National Defense Research Committee facilities at Bruceton.

The Carnegie Group (C.I.T.) employed some outstanding researchers which contributed much of the current shaped charge knowledge. The leaders at Carnegie were R.V. Heine-Geldern, N. Rostoker, Emerson Pugh, and his student, Robert Eichelberger (a former Director of BRL).

In addition to the work at C.I.T., important post-war contributions to shaped charge research were made by L. Zernow and associates at BRL. Other laboratories making important contributions during this time period were the Naval Ordnance Laboratory, Maryland (Solem and August), the Naval Ordnance Test Station, California (Throner, Weinland, Kennedy, Pearson, and Rinehart), Picatinny Arsenal, New Jersey (Dunkle), the Stanford Research Institute, California (Poulter), and others. Additional developments in shaped charge technology, especially on the West Coast, are presented in Kennedy (1983).

Excellent bibliographical and historical information is provided in Birkhoff (1947), Parker (1950), and NRDC (1945). Ayton et al. (1955) is somewhat more recent. This bibliography contains references, with informative abstracts, to all pertinent literature found in books, periodicals, and reports on the subject of shaped charges, particularly their military applications. The time frame covered is basically 1930 - 1954, although some earlier backg ound material has been covered.

The shaped charge principle was clarified and understood as a result of the pioneering flash x-ray photographs taken in the U.S. by Seely and Clark (1943), Clark and Rodas (1945) and in the U.K. by Tuck (1943). Schumann and Schardin obtained similar flash radiographs in Germany in 1941 (Birkhoff 1947; Schumann 1945; Schardin and Thomer 1941). Birkhoff (1947) and Schumann (1945) discuss the "angry priority controversy" over the first flash radiograph. X-ray photographs (or flash radiographs) are necessary since ordinary photographs are uninformative due to the smoke and flame associated with the detonation. See also Clark (1949).

Schardin and Thomer (1941) published excellent flash radiographs of collapsing shaped charges with hemispherical liners. These x-ray photographs clearly depict the collapse of the hemispherical liner (as it "turns inside out from the pole") and illustrates the "pinch-off effect" as the equatorial region of the liner collapses on the jet. The liner was truncated from the equator to remove this "pinch-off." These phenomenon were rediscovered some 30 years later.

The Roentgenblitz or flash x-ray is made possible by the very brief discharge of a high voltage x-ray tube. The basic apparatus was developed by Dr. Slack of Westinghouse Electric Company (Simon 1947).

Also, Linschitz and Paul (1943) experimentally studied conical lined shaped charges in differen stages of collapse. Hand tamped nitroguanidine of various densities was used as the explosive fill to achieve a partial collapse of the liner. The conical liner was recovered in water after a partial deformation, the degree of liner deformation (or collapse) corresponding to the density of the explosive fill. The results showed excellent agreement with the flash x-ray photographs.

Based on the analysis of the flash x-ray data and the partial collapse studies (Linschitz and Paul 1943), analytical models of the collapse of a lined conical shaped shaped charge were developed and verified by Birkhoff (1947, 1943), Birkhoff et al. (1948), Evans (1950), Tuck (1943) and Pugh et al. (1952).

A bibliography and account of the weaponization of the shaped charge and similar principles are given in Backofen (1980a, 1980b, 1980c) and Backofen and Williams (1981a, 1981b, 1981c). Backofen's bibliography is extensive, especially regarding foreign sources. Earlier, World War II time frame results and bibliographical information are given in DM-1 (1947), Parker (1950), NRDC (1945), Ayton et al. (1955), Hill et al. (1944), and NDRC (1946). The time line charts given in Walters and Zukas (1989) highlight the major events in shaped charge advancement.

Shaped charge theory continued to develop during the 1950s, boosted by the Korean War (Cook 1958; Kennedy 1983; Berkholtz 1988; Walters 1986; Walters and Zukas 1989; Thomanek 1959, 1960; Kolsky et al. 1949; Kolsky 1949; Evans and Ubbelohde 1950a, 1950b; Pugh et al. 1951; and Koski et al. 1952). During this time period, tremendous progress was made toward the understanding of the phenomena associated with shaped charge jets. Improved flash x-ray techniques were employed to observe the jet process and analytical models were improved. Efforts were made to improve existing shaped charge liners; to use detonation wave shapers; to provide spin compensation via fluted liners; to provide shaped charge follow-through mechanisms; and to enhance the overall system performance. Moses (1957) filed a U.S. patent on wave shaping and follow-through concepts for a shaped charge munition. Also, slugs from shaped charge firings were recovered and metallographic analyses were performed by Desphande and Singh (1959) and Singh et al. (1959). Jet temperature effects were examined by Robinson (1957) and the effect of environmental pressure and temperature on shaped charge jet formation and performance was studied by Reed and Carr (1950). Birkhoff (1947) discussed many of the problems still being studied today and additional information is given in Walters and Zukas (1989).

Starting in the 1950s and 1960s, significant shaped charge developments were made possible by the perfecting of experimental techniques such as high speed photography and flash radiography. Other improvements resulted from the transition from TNT to more energetic explosives, i.e., from TNT to Comp B to Octol and then to pressed explosives, notably LX-14. Also, alternate modes of initiation (other than point-initiation) and wave-shaping techniques have provided warhead design improvements. Other advances stemmed from the development of large computer codes to simulate the collapse, formation, and growth of the jet from a shaped charge liner. Numerical techniques and the advantages and limitations of various computer codes for wave propagation and penetration studies are discussed in detail in Walters and Zukas (1989). These codes provide, for the most part, excellent descriptions of the formation of the jet.

Currently, shaped charge research continues in order to devise a successful countermeasure to the advanced armors currently fielded and/or contemplated, see e.g., Kennedy (1985). Studies which originated in the 1950s still continue; notably, torpedo applications of shaped charge rounds, anti-aircraft rounds, fragmentation rounds, multi-staged or tandem warheads, long standoff rounds, non-conical liners, and non-copper liners. Also, metallurgical and chemical aspects of the liner material as well as methods of liner fabrication remain important.

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